

BIOLOGICAL WEAPONS AND ECOLOGY: PUBLIC IMAGERY

Robert H. Haynes 1)

Introduction:

Deliberate attempts to inflict infectious disease on enemy troops or civilians seem to have occurred only on a few occasions in the long history of human aggression²⁾. Incontrovertible instances in which biological weapons (BW) have been used in modern war are extremely rare, even though many advances have been made in the technologies for growing and handling pathogenic bacteria ever since Robert Koch's epochal work on anthrax in 1876.

The Geneva Protocol of 1925 prohibited the use of biological as well as chemical weapons. However, research, development, testing and stockpiling of bacteriological weapons, as well as contingency plans for their use, did proceed during World War II, and they were employed by Japanese against Chinese in the early forties³⁾. Thus, the Biological Weapons Convention (BWC) of 1972 which, among other controls, required the destruction of existing weapons, and was ratified or signed by over one hundred states, has been hailed as the world's first significant disarmament treaty⁴⁾.

The 1972 BWC contains potential loopholes. However, I doubt if there can be any written set of rules, agreement or constitution that is immune to subversion by committed nitpickers, or those more concerned with the letter than the spirit, or obvious intent, of the language used. If you are determined to disobey an inconvenient law, a clever lawyer will be able to find a loophole through which you may escape; and he will concoct a sophistry in your defence should you have the bad luck to be indicted instead.

A more serious problem with the BWC is not that it contains loopholes, but that it would be physically impossible to verify full compliance even with the most explicit and unambiguous legal prohibitions. In this area it is notoriously easy to cheat. Research and development related to offensive biological weapons can be carried out inconspicuously in small laboratories, or even openly in institutes of public health or under the guise of 'defence' in military and industrial installations. Any reasonably industrialized country should be able to camouflage in ordinary fermentation plants the production of significant quantities of pathogens and toxins which could be used for malevolent purposes. However, as Freeman Dyson has pointed out, using the 1972 BWC as a specific example, arms control agreements do not have to be perfect in order to be valuable⁵⁾. Treaties controlling biological weapons do not become useless as soon as they are violated. The choice is not between imperfect and perfect treaties; it is between an imperfect agreement and none at all. Without a treaty of some kind there would not even

exist legal grounds for international protest against violators. If it is argued that to be useful, the BWC must be fully verifiable in practice, human judgement is rendered subordinate to technology. A rigorous verification regime would entail the establishment of a costly bureaucracy and a system of unannounced, unchallengeable inspections. This would generate massive amounts of 'intelligence' data which may or may not lend themselves to correct interpretation. The value even of an unverifiable arms control treaty is that it contributes to the establishment of a world order based on mutual interest and common sense, rather than confrontation. It becomes itself an important confidence building measure within the global village. However, this does not imply that efforts to strengthen the 1972 BWC should be abandoned. I suggest only that this initiative is not as urgent as negotiations on the reduction of conventional arsenals and the elimination of the international arms trade.

Problematic Aspects of Biological Weapons:

Several reasons have been advanced to account for the unpopularity of biological weapons, even as a deterrent. The most oft-quoted are that they are singularly immoral, impractical or ungentlemanly tools of war, in curious contrast to conventional weapons⁴⁾. However, astonishing developments in genetic engineering and biotechnology have occurred since the preparation of the first recombinant DNA molecules in 1972. Thus there is a possibility, albeit remote, that with the aid of this new technology versatile and effective biological weapons might yet be developed^{3,6,7)}. I will refer to these conceptualized weapons as 'novel', to distinguish them from the very real ones that have utilized naturally occurring pathogens such as anthrax spores.

Great excitement and concern has been generated in various communities - political activist, military, and arms control - over novel biological weapons however speculative and implausible their realization might be⁸⁾. This would suggest that considerations of international law, morality and military etiquette are considered inadequate to provide any credible assurance that national leaders will eschew the development and use of biological weapons if they ever are thought to be tactically effective in battle and therefore strategically advantageous in diplomacy. Certainly the spectre of gross cruelty is unlikely to inhibit their use. Torturers, soldiers and physicians alike report that to be burnt to death is perhaps the most horrible way to die, yet flame-throwers and napalm bombs have been used extensively in recent wars and occupy a prominent place in the arsenals of the world today.

It is difficult to avoid the cynical conclusion that widespread ratification of the 1972 BW Convention was based primarily on the fact that natural pathogens are too slow acting, unreliable and uncontrollable in their effects to be used by anyone except terrorists. What, then, is there to restrain

nations from embarking on a race to develop the supposedly useful and effective weapons that haunt the imagination of biotech enthusiasts both within and without the military/industrial complex? A possible answer, and the one that I shall develop here, is suggested by the marked contrast in the intensity and persistence of human reaction against nuclear as opposed to incendiary attacks on cities. The kill rate for people burnt to death in the horrible fire-storms produced by conventional bombs first in Hamburg and subsequently in Dresden and Tokyo, appears to have been roughly comparable to the rates attained with nuclear weapons in Hiroshima and Nagasaki⁹⁾. In terms of total killed, it has been estimated that 140,000 people in Hiroshima had died of injuries by the end of 1945 whereas 150,000 were killed in Dresden¹⁰⁾. It is sobering to recall that latter-day analysts generally concede that this enormous slaughter was not of much strategic significance in determining the outcome of World War II. However, the psychological scars left on survivors of the nuclear attacks were very severe¹¹⁾. Antipathy toward nuclear weapons far transcends concern over their physical consequences, because at some unknown concentration in the environment radioactivity becomes an ecological peril¹²⁾.

Public Opposition to Nuclear Technology:

Outrage against nuclear weapons, and the peaceful uses of atomic energy, persists unabated today. It is based primarily on deep concern over the long term genetic and environmental effects of radioactivity released in weapons programs and from accidents at nuclear power stations^{12,13)}.

The fallout from an 'average' one megaton nuclear ground burst would produce serious radioactive contamination over an area of roughly 1000 square miles¹⁴⁾. The dust lofted into the stratosphere would deposit long lived fission products worldwide. People would continue to die of radiation induced cancer years later, and many children would be born with serious birth defects. It would be virtually impossible to decontaminate the soil. A sufficiently severe exchange could lead to 'nuclear winter' and the extinction of most higher organisms on earth. On the other hand, the damage resulting from fire-storms, however, dreadful, is not long lasting. No genetic or irreparable environmental effects are produced. The physical damage can be cleaned up fairly quickly. Despite the holocausts at Dresden and Tokyo there unfortunately is little or no organized opposition to incendiary weapons.

The environmental damage resulting from radioactivity released even from major accidents at nuclear power stations, or at other points in the nuclear fuel cycle, is of course minor in comparison with that which would be associated with the use of contemporary nuclear weapons. But most people cannot, or do not, make such delicate quantitative comparisons. It is hardly surprising that there is such strong emotional support for the anti-nuclear movement throughout the world. The economic

benefits of nuclear power are very great, the safety record of the nuclear industry in western countries is highly commendable, and properly managed nuclear power stations are much cleaner environmentally than fossil fuel plants¹⁵⁾. In Canada at least, technology for the permanent, safe disposal of nuclear fuel wastes is well in hand¹⁶⁾. However, people associate nuclear energy with nuclear weapons and their apocalyptic environmental hazards. As a result, it is unlikely that the benefits of nuclear technology will ever be fully realized in the foreseeable future.

The Ultimate Folly of Biological Weaponeering:

The rapidly developing biotechnology industry may well suffer the same fate as the nuclear industry if two public perceptions arise, however wrongly based they might be. The first would be that genetic engineering techniques can be used to produce novel biological weapons. The second would be that even the accidental release of genetically engineered pathogens into the environment could cause permanent ecological damage. In this connection it is sobering to recall the fears that have arisen in recent years over the field testing of genetically engineered organisms to assess their value for pest control and other agricultural purposes.

It is extremely unlikely that novel biological weapons, even if they could be produced, would be any more effective or useful militarily than those employing natural pathogens⁸⁾. Thus it is doubly foolish for governments to allow military or industrial laboratories to dabble in this area. To claim that the research is being done for purely defensive purposes, even if true, is politically counter-productive, especially if it is carried out in closed laboratories. It is evident that many people no longer believe the reassurances offered by government agencies that mysterious new technologies are safe. The sceptical response to official pronouncements made in connection with the proposed release of genetically engineered bacteria at Monterey, California, in 1986 should make this abundantly clear to anyone in touch with public sensitivities today¹⁷⁾. Thus, the ultimate folly of biological weaponeering resides not in the vague possibility that novel weapons might actually be developed and used. It is rather that a public aroused by the prospect of a new source of environmental degradation might hobble, or even foreclose, the further development of biotechnology for applications in medicine, agriculture and pollution control.

The Release of Genetically Engineered Pathogens:

Possible sources for the release of genetically engineered pathogens are much the same as for naturally occurring biological warfare agents such as anthrax spores. Apart from the deliberate dispersal of large quantities of such organisms during hostile actions, smaller amounts will escape from research laboratories

and manufacturing plants, from field testing sites, and as a result of accidents during weapons transport by land, sea or air. Experience with nuclear weapons would suggest that escape from production facilities and during transport poses the greatest risk, though I cannot be sure of this as much of the relevant information is difficult to obtain. Two consequences of the dissemination of genetically engineered pathogens must be considered, even though their discussion must be almost entirely speculative. They are first, public reaction to any prospect of release, and second, the physiological and ecological impact of the infectious spread of novel genes, engineered for use in weapons, into other organisms. On the basis of my experience with the Canadian nuclear energy program and also with molecular genetics, the former is by far the more serious of these concerns.

I must now enter terra incognita. Apart from analogy with the history of nuclear technology, my only possible guide derives from public responses to the test release of other genetically engineered organisms, and from preliminary attempts by ecologists to assess the risks of such trials. Detailed discussions of both issues can be found in the book edited by J.R. Fowle¹⁷.

For the sake of argument, let us now accept the possibility that 'improved' biological warfare agents can be created through the use of recombinant DNA technology. It then seems reasonable to assume that, once this fact becomes widely known, the public outcry against biotechnology would be vastly more severe than that which occurred in the non-military situations described in Fowle's book. However, because of the complexity of microbial ecosystems, among other reasons, the long term ecological consequences of the release of such organisms will remain virtually impossible to assess, both in theory and in practice.

In recent years, safety concerns over genetically engineered organisms have shifted from the laboratory to the environment. Thus, I am surprised that little mention has been made of the environmental impact of novel biological weapons by those concerned with arms control. The guiding principle behind the initial (1976) guidelines on recombinant DNA research issued by the U.S. National Institutes of Health (NIH) was containment. Fears had been expressed by leading molecular biologists that the introduction of foreign genes into bacteria might transform the host into an epidemic pathogen¹⁸. An important element in the containment policy was the prohibition of experiments involving large scale cultures (greater than ten litres). By restricting culture volumes, the probability of effective environmental inoculation as a result of accidents might be reduced. As experience with recombinant DNA increased, containment rules were relaxed. The revised NIH guidelines issued in 1982 allowed the release of large quantities of genetically engineered organisms into the environment under a complex system of prior notification and approvals by relevant authorities.

In 1983 permission was given to a group at the University of

California, Berkeley, to conduct field tests in Monterey, California, of two soil microorganisms from whose genomes a specific DNA fragment was deleted. This fragment encodes a protein that provides a nucleation point for ice on the bacteria. It was hoped that these so-called 'ice-minus' strains would serve to reduce the temperature at which frost forms on potato and strawberry plants, as well as other crops. It is interesting to recall that one concern raised over this proposal was that local patterns of rainfall might be altered as a result of the release. The activist Jeremy Rivkin, supported by two environmental organizations, brought national attention to the issue by filing a lawsuit against NIH on the grounds that approval was given for the test prior to a full study of its environmental consequences. The fact that it simply is not possible, on the basis of present knowledge, to assess such consequences prior to release is interesting to say the least, in the context of biological warfare agents. In addition, twenty-seven 'green' members of the West German parliament wrote to the Monterey County Board of Supervisors advising the board to forbid the tests: the issue thus became one of international environmental significance. One Monterey resident wrote to the local newspaper that "the new technology conjures up images of a science fiction thriller where the creation of mad scientists threatens the delicate balance of nature and our ecosystem". Local farmers in Tulare, California, where a similar test was proposed, feared that the public might boycott farm products from the area by associating the release of genetically engineered organisms with events like the nuclear reactor accidents at Chernobyl and Three Mile Island in Pennsylvania. Public assurances by NIH and the U.S. Environmental Protection Agency (EPA) were of no avail. Local residents recalled EPA's earlier approval of a pesticide (DBCB) which proved to be a carcinogen and caused sterility among male factory workers.

This and other recent incidents clearly shows, as Krinsky has concluded¹⁷⁾, that public perception of biological risks has shifted from human health to ecology. It does not take much imagination to predict the ferocity of public opposition that would be directed against biotechnology should it be widely and convincingly advertised that genetic engineering was being used to develop novel biological weapons. Public perceptions of the hazards associated with nuclear power are out of all proportion to the known actuarial risks of injury borne by workers in the industry or those living near reactors^{15,19)}. However, it is clear that these qualitative perceptions count for much more politically than the calculations carried out by experts in risk analysis. Indeed, it recently was found in Taiwan that public opposition to nuclear power actually increased after authorities launched an extensive public education program designed to alleviate nuclear fear²⁰⁾. It takes more than facts and expert opinion to allay public concern today over the dark sides of modern technology, especially where the possibility of environmental damage may be involved.

What can be said scientifically about the possible

ecological consequences of the release of genetically engineered organisms, whether they are pathogens or not? Unfortunately, the answer is 'not much'. Microbial ecology is an extraordinarily complex subject about which little is known. In comparison with microbial genetics, it is still in its infancy. The paucity of research in this area is surprising in view of the overwhelming metabolic importance of earth's microbiota in maintaining the global biogeochemical cycles which make possible the existence of the biosphere itself²¹⁾. In 1986 an EPA study group on biotechnology stated categorically that the principles governing the dispersal and persistence of genetically engineered organisms in the environment are not known. Only after such principles are discovered would it be possible to develop reliable risk assessments. However, it is by no means clear that any such hypothetical principles upon which a 'predictive ecology'¹⁷⁾ could be based are in fact discoverable, or even that they exist¹⁷⁾.

There are two fundamental questions of microbial ecology which must be considered here. First, what is the likelihood that an organism containing recombinant DNA might become established in the environment and cause ecological damage? Second, what is the likelihood that recombinant (or other) genes from this strain might spread 'horizontally' in the community and become incorporated into the genomes of natural forms of this species or even other genera? These questions have been considered in some detail by Sharples²²⁾ and Lenski²³⁾ respectively.

Sharples' paper summarizes her review of the extensive, but anecdotal, information that became available after various foreign species (not limited to microorganisms) had been introduced, by accident or design, into new environments. She concluded that even with such information it is not possible to predict whether any particular species might become established and spread. Only a small fraction of introduced species are known to have caused ecological disruptions but it would not be possible to predict which ones could cause problems without an ecological evaluation directed at the specific organisms and specific environments before release. This implies that one would have to possess detailed knowledge of the biology of the new strains and of the structure of the particular biotic community into which they would be released. It also implies that one would have to carry out field tests of novel biological warfare agents in environments closely similar to those in which they were to be used before their incorporation into weapons. In view of the fact that total containment can never be assured in such tests it is clear that they would be unethical in the extreme. They could hardly be approved by any scientifically or morally responsible authorities.

A number of objections have been raised against the validity or relevance of 'introduced species' models in ecological risk assessment. Some of these objections have been based on classical evolutionary concepts, even though these ideas, being so very general, are of little use in making specific a priori

predictions about organismal and ecosystem evolution²⁴⁾. In her paper Sharples meets these objections with specific counter-examples from the literature; her findings do not need to be repeated here. One of the evolutionary arguments used in this context is the so-called 'excess baggage' hypothesis. It is argued that 'plasmid carriage' reduces the fitness of host bacteria in the absence of selection for some function borne by the plasmid. Without such selection, the bacteria/plasmid association traditionally was thought to be less fit than the host itself and accordingly would soon disappear from the environment. Recently, however, Bouma and Lenski²⁵⁾ have shown that host genomes can themselves adapt to the plasmids they carry and exhibit an increased fitness with respect to plasmid-free hosts. These observations argue against the presumed generality of the 'excess baggage' hypothesis. Plasmids carrying, for example, toxin genes might well infect other potential hosts in the environment and thereby increase the fitness of the new association.

Lenski reviewed the various mechanisms for 'horizontal' gene transfer among bacteria. These processes, so far studied almost entirely under controlled conditions in the laboratory, are mediated by viral transduction, conjugative plasmids, bacterial transformation, transposition, and viral and plasmid recombination. The importance of such infectious spread of genes in higher organisms is not clear. However, the Ti plasmid of Agrobacterium tumefaciens can become incorporated into the genomes of infected plants and can be used to mediate the transfer of genetic material from one species to another²⁶⁾. Rates of gene transfer between species are highly variable and so it is impossible to say how likely such transfers are in general. The likelihood of adverse consequences is related to the fitness and number of organisms introduced. The dynamics of the infectious spread of foreign genes depends on the intrinsic rate of gene transfer and the population densities of both donor and recipient species. Thus, the ecological consequences of small scale accidental releases of pathogens as a result of laboratory accidents could be very different from those caused by the deliberate release of the many tons of pathogens that²⁷⁾ presumably would have to be used in a wartime biological attack. Thus, the deleterious effects of novel microorganisms in the environment bear a certain resemblance to those of radioactivity: minute environmental 'doses' arising from minor laboratory accidents may be relatively harmless, whereas large 'doses' arising from the use of biological weapons may be very dangerous, not only to those exposed but ultimately to the biosphere itself.

The basic conclusions of those ecologists who have considered the release of genetically engineered organisms is that risk assessment must be carried out on a 'case by case' basis²³⁾. The complexity and heterogeneity of ecological systems, and the ability of populations to evolve, makes it impossible to arrive at any generalizations regarding the probable ecological risks of novel biological warfare agents. However, there is no reason to think they would be trivial.

Furthermore, the effects would not remain localized in time or space inasmuch as even traditional agents such as anthrax spores have been shown to persist for decades in the soil²⁸⁾ and impermeable geographic barriers to microbial dispersal are not known to exist.

Mythic Roots of Nuclear and Genetic Fear:

To understand why people are so deeply concerned over the ecological consequences of the release of radioactivity and genetically engineered organisms into the biosphere, it is informative to examine and extend some recent psychological analyses of the origin of nuclear fear²⁹⁾. Nuclear winter and the prospect of a world poisoned by nuclear fallout terrify people and are feared more than fire¹²⁾. People are familiar with fire, gunpowder, and chemicals, whereas radiation is mysterious. The release of nuclear energy from the heart of the atom is seen as a black art. It conjures images of the alchemist and the transmutation of nature by Faustian man. In his profound study of the development of nuclear weapons, Spencer Weart has argued, persuasively I think, that these mythic symbols, which lie deep in the psyche of Western man, constitute the psychological source of nuclear fear¹³⁾. The fact that nuclear energy is coupled also with promises of inexhaustible sources of cheap energy and magical cures for cancer and other diseases is powerless to ameliorate anxieties that derive from such profound cultural sources.

There are striking historical parallels between the scientific careers of the atom and the gene, their reification in nuclear and genetic engineering, and the promises and perils associated with them³⁰⁾. The atom and the gene first entered science as purely hypothetical entities useful in accounting for certain quantitative features of chemical combination and the transmission of hereditary traits. In this century, laboratory research established that atoms and genes were no mere mathematical constructs. They were shown to correspond to dissectable, and ultimately visible, units of structure in the world around us. Metaphysics passed into physics with the reification of atoms and genes. They could be identified, weighted, measured, counted, synthesized and transformed by scientists. What were once fabulous beasts in the mythic landscape of the mind were domesticated in laboratories throughout the world. The reality of these microscopic structures, and our ability to manipulate them, made possible the development of both nuclear and genetic technologies. Utopian visions of limitless energy, abundant food and medical marvels flowed from these amazing developments. But so did nuclear weapons, Andromeda strains and the prospect of Armageddon: nuclear winter and global pandemic, leading equally to the destruction of the biosphere of which we are both part and product. To the average person for whom atoms and genes lay at the heart of the deepest mysteries of life and the universe, scientists had passed from craftsmen to saviors to sorcerers.

Science was more to be feared than trusted. After all, had not some of the most eminent scientists deliberately adopted the language of the alchemist? Was it mere coincidence that Frederick Soddy, Ernest Rutherford and H.J. Muller, all Nobel Laureates, used the alchemical word 'transmutation' to describe their discoveries in atomic physics and genetics³¹⁾?

Fear is a more primitive emotion than hope. It elicits the powerful physiological drive to 'flight or fight'. Fearful wars are commonplace in human history. On the basis of Weart's analysis of the origin of nuclear fear, and my extension of it to genetic fear, the future of biotechnology may come to be as bleak as that of nuclear technology, especially if genetic engineering should ever be used in attempts to construct novel biological weapons.

Conclusion:

A more robust international protocol against biological weapons, more or less along the lines suggested by Susan Wright and many others⁹⁾, should be put in place as soon as possible. To allow arms control negotiations over biological weapons to drag on interminably is a mistake. The natural public reaction to such a spectacle will be to suspect that 'where there is smoke, there must be fire': perhaps novel biological weapons really are being designed somewhere by someone? Verification mechanisms based on challenge inspection at short notice, together with sanctions against violations, should be included in the new treaty. However, for reasons of cost, as well as to avoid exciting unnecessary public fears, the verification organization should be kept small. If the 'cold war' really is over, this and other confidence building measures should be politically attainable. My reason for urging prompt action is not that I believe that the matter is immediately urgent, or that a race to develop novel biological weapons is imminent. Rather, it is to enable arms control agencies to concentrate their resources on the much more serious and obvious dangers posed by the continuing proliferation of conventional, nuclear and chemical weapons.

Notes and References:

- 1) Department of Biology, York University, Toronto, Ontario, Canada, M3J 1P3.
- 2) O'Connell, R L 1989: Of Arms and Men, (Oxford University Press: New York).
- 3) Geissler E (ed) 1986: Biological and Toxin Weapons Today, (Oxford University Press: Oxford).
- 4) Gizewski P 1987: Biological Weapons Control, Issue brief number 5, (Canadian Centre for Arms Control and Disarmament: Ottawa).
- 5) Dyson F 1984: Weapons and Hope, (Harper and Row: New York).
- 6) Wright S 1985: The military and the new biology, Bull.

- Atomic Scientists 41, 10-16.
- 7) Wright S 1990: Preventing a Biological Arms Race, (MIT Press: Cambridge, MA).
 - 8) Novick R and Shulman S 1990. New forms of biological warfare?, chapter 5 in Wright note 7.
 - 9) Rhodes R 1986: The Making of the Atomic Bomb, (Simon and Schuster: New York).
 - 10) Schroeder D 1984: Science, Technology and the Nuclear Arms Race, (John Wiley and Sons: New York).
 - 11) Lifton R J 1968: Death in Life: Survivors of Hiroshima, (Random House: New York).
 - 12) Schell J 1982: The Fate of the Earth, Alfred A. Knopf: New York).
 - 13) Weart S R 1988: Nuclear Fear, (Harvard University Press: Cambridge, MA).
 - 14) By way of comparison the yields of the Hiroshima and Nagasaki fission bombs were 0.0125 and 0.022 megatons of TNT equivalent, respectively. Fusion bombs of 20 and 58 megatons have been tested by the US and USSR respectively. In the early eighties it was estimated that there existed about 50,000 nuclear warheads in the world with a total explosive yield of 20,000 megatons.
 - 15) Hare F K 1988: The Safety of Ontario's Nuclear Power Reactors. Report to the Minister of Energy for the Province of Ontario, (Government of Ontario: Toronto), vol. I, 288 pp.
 - 16) Dormuth K W (ed) 1987: Radioactive Management and the Nuclear Fuel Cycle, vol. 8, numbers 2 and 3 (two special issues on the Canadian Nuclear Fuel Waste Management Program). For a non-technical description of this program see "Managing Canada's Nuclear Fuel Wastes", Atomic Energy of Canada Ltd. Report WWM-89-05-01.
 - 17) Krimsky S 1987: Gene splicing enters the environment: the socio-historical context of the debate over deliberate release. In Application of Biotechnology: Environmental and Policy Issues (J.R. Fowle III, ed), American Association for the Advancement of Science Selected Symposium 106 (Westview Press: Boulder, CO).
 - 18) Watson J D and Tooze J 1981: The DNA Story, a documentary history of gene cloning, (W.H. Freeman and Company: San Francisco).
 - 19) Upton A C 1982: The biological effects of low-level ionizing radiation, Scientific American 246, number 2, 41-49.
 - 20) Hamilton D P 1990: Fear and loathing of nuclear power, Science 250, 28.
 - 21) Rambler M B, Margulis L and Fester R 1989: Global Ecology, (Academic Press: San Diego, CA).
 - 22) Sharples F E 1987: Application of introduced species models to biotechnology assessment, in Fowle J R, note 17 supra.
 - 23) Lenski R E 1987: The infectious spread of engineered genes, in Fowle J R, note 17, supra.
 - 24) Haynes R H 1991: Modes of mutation and repair in evolutionary rhythms, in Symbiosis as a Source of Evolutionary Change (Margulis L and Fester R, eds), (MIT Press: Cambridge, MA), in press.

- 25) Bouma J E and Lenski R E 1988: Evolution of a bacteria/plasmid association, *Nature* 335, 351-352.
- 26) Horsch R B, Fraley R T, Rogers S G, Sanders A L and Hoffman N 1984: Inheritance of functional foreign genes in plants, *Science* 223, 496-498.
- 27) Burnet Sir M 1962: *Natural History of Infectious Disease*, (Cambridge University Press, Cambridge), pp. 364-366.
- 28) Geissler E 1983: Implications of genetic engineering for chemical and biological warfare, in *World Armaments and Disarmament*, SIPRI Yearbook, (Taylor and Francis: London).
- 29) Russett B 1989: Democracy, public opinion and nuclear weapons, in *Behavior, Society and Nuclear War*, vol 1, (Tetlock P E, Husbands J L, Jervis R, Stern P C and Tilly C, eds), (Oxford University Press: New York).
- 30) Haynes R H 1989: Genetics and the unity of biology, presidential address XVIth International Congress of Genetics, *Genome* 31, 1-7.
- 31) Soddy F 1904: Radioactivity, ('The Electrician' Printing and Publishing Company: London), pp. 93-94. Rutherford E 1937: *The Newer Alchemy*, (Cambridge University Press: Cambridge). Muller H J 1927: Artificial transmutation of the gene, *Science* 66, 84-87.